ENHANCEMENT OF IMAGE RECOGNITION IN DIGITAL CLOSE-RANGE PHOTOGRAMMETRY USING MATHEMATICAL EQUATIONS AND CAMERA CALIBRATION

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ABSTRACT

The use of close-range photogrammetry technique via mathematical modelling and camera callibration are becoming an interesting area in reverse engineering to describe relationships between spatial objects in various applications. It has been used as an alternative solution to conventional methods for generation of virtual 3D models, which for use in CAD, CAM and CAE studies. However, many studies have revealed that most of the developed algorithms for 3D modelling possess several major challenges due to its tedious task during the image recognition phase. Thus, this research focuses to investigate the model reconstruction process for an enhanced image capturing method using close-range photogrammetry. Mathematical equations are presented to potentially help for an effective modelling operation as they are used to define the appropriate parameters for shooting phase based on the object's size. This is to obtain as sufficient number of images as possibile to increase the overall overlapping areas between images during the photogrammetric data acquisition period. This research used different types of camera sensors and calibrations to capture the images respect to the reconstructed 3D models are presented. Finally, this research proposed a thorough framework incorporated in data acquisition factors and mathematics equations to capture a set of images using smartphone camera for close-range photogrammetry. The feasibility of the framework for generating a 3D model using photogrammetry was verified with a 3D model generated using ATOS 3D Scanner (high resolution 3D scanner for reverse engineering). Results obtained showed that the photogrammetric model reaches accuracy of 99% with the model scanned using ATOS along with maximum and minimum errors of 0.0003 m and 0.0004 m respectively. With that, using the same photogrammetric settings three case studies of different object sizes were investigated. At the end of this study, the objective of an enhanced image capturing method is successfully achieved.

ABSTRAK

Penggunaan teknik fotogrametri jarak dekat dengan menggunakan model matematik dan tentu-ukur kamera menjadi suatu bidang yang semakin menarik di dalam kejuruteraan pembalikan untuk menerangkan hubungan antara spatial objek di dalam pelbagai aplikasi. Ia telah digunakan sebagai penyelesaian alternating bagi teknik konvensional untuk membentuk sebuah model 3D, di mana ia digunakan di dalam kajian CAD, CAM dan CAE. Waimapun, terdapat banyak kajian yang menunjukkan bahawa kebanyakan kemajuan algoritma untuk permodelan 3D mempunyai beberapa cabara disebabkan oleh fasa mengenalpasti imge dan ianya merupakan tugas yang mencabar. Maka, kajian ini bertujuan untuk mengkaji proses pembinaan semula model untuk memperbaiki cara mengambil gambar dengan menggunakan teknik fotogrametri jarak dekat. Persamaan matematik diperkenalkan yang berpotensi untuk menyumbang operasi permodelan yang efektif dengan mengenalpasti parameter yang sesuai bagi fasa pengambilan gambar berdasarkan saiz objek. Hal ini bertujuan untuk memperoleh bilangan gambar yang mencukupi bagi meningkatkan ruang pertindihan antara gambar-gambar. Kajian ini juga menggunakan tiga sensor kamera yang berlainan semasa pengambilan gambar-gambar tersebut dan hasil pembentukan model 3D dinyatakan. Akhirnya, kemampuan rangka kerja untuk menghasilkan model 3D dengan menggunakan teknik fotogrametri telah dibuktikan dengan model 3D yang dihasilkan menggunakan pengimbas ATOS 3D (pengimbas 3D resolusi tinggi untuk kejuruteraan pembalikan). Keputusan yang diperolehi oleh model fotogrametri memcecah ketepatan 99% dengan pengimbas model menggunakan ATOS bersama kesilapan maksimum dan minimum sebanyak 0.0003 m dan 0.0004 m. Justeru itu, tiga objek yang berlainan saiz telah dikaji dengan menggunapakai tetapan fotogrametri yang sama. Hasil kajian mendapati objektif untuk memperbaiki cara pengambilan gambar melalui teknik fotogrametri tercapai.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_H	-	Acquisition height
A_R	-	Acquisition row
!!!	-	Total distance of acquisition
!!!	-	Shooting distance
C_o	-	Perimeter
C_c	-	Circumference of the camera movement
d_o	-	Diameter of object
f	-	Focal length
H	-	Height of the object
H_i	-	Height of the object's image
M	-	Magnification
N_T	-	Total number of arcs formed
P_o	-	Percentage of overlapping
P_I	-	Percentage of image size
r	-	Shooting distance
S	-	Arc length of camera's movements
S_c	-	Arc of camera's movements
w_o	-	Width of rectangular object
S_c	-	Arc of camera's movements
θ_c^o	-	Angular camera rotation
θ_V^o	-	Angle of view

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CHAPTER 1

INTRODUCTION

1.1. Preliminary

Photogrammetry is an engineering code of practice that has spread by the impact of revolution in automation, computer systems and related technologies (Linder, 2003). Therefore, the drastic increment in the used of computers has facilitated on the used of photogrammetry techniques. This can be perceived through a perceptible trend shift from analog to logical reasoning and digital techniques in various fields, especially in the industries (Schenk, 2005). The word 'Photogrammetry' is derived from the old Greek words, *phot*, *gramma* and *metrein*, meaning light, drawing and measurement respectively (Linder, 2006; Walford, 2017). Fundamentally, the photogrammetry method is the science of acquiring genuine surface information on the texture and characteristics of a physical object. The technique is executed without subjecting any direct touch on the object of interest but rather through approaches such as recording and taking a set of photographic images using digital cameras (Stoian, 2014).

Moreover, the progression of the photogrammetry techniques have become an alternative substitute in the image-based modeling and rendering (IBMR) approaches. It is a faster technique in data gatering compared to the laser scanner or conventional approches, it offers a huge amount of points and the processing time is much lower (Quan, 2010). Both scanner lasers and conventional methods are a real options for 3D modeling for reverse engineering but each one of them can not be applied in all cases. On the other hand, photogrammetry can be applied in all cases with many advantages (Rashidi A et al., 2013). Additionally, photogrammetry techniques are categorized into two groups of far-range, which branches into aerial and terrestrial techniques and close-range secondly as portrayed in (Barsi, 2010).

There has always been an existing break that defines, as a technological gap between the recent discoveries in digital modelling methods and the application of these methods that can predominantly penetrate into the business markets. The photogrammetry has become a significant part and solution to technological term, whereby several organizations such as American Society for Photogrammetry and Remote Sensing (ASPRS), International Society for Photogrammetry and Remote Sensing (ISPRS) and Committee for Documentation of Cultural Heritage (CIPA) are currently attached actively with the photogrammetry developments (Walford, 2017).

Consequently, research institutes, research departments, universities, and certain mega industries are the only community that exploits the transition to these new emerging digital photogrammetry techniques. In general, the use of conventional methods have been replaced by the photogrammetry in the last decade, due to its easy handling and intensive data provided. These limitations mean that many times it will not be the best option (in addition to its high cost). Photogrammetry offers exceptional performance as to the amount of data provided in a short time in engineering works or reverse engineering (Stoian, 2014). Therefore, photogrammetry techniques are becoming a more widely studied approach due to its advantages for various applications. This can be seen from the beginning of the first invention stage to the stage of available and workable photogrammetry application as illustrated in Figure 1.1 (Nguyen et al., 2012; Schenk, 2005).

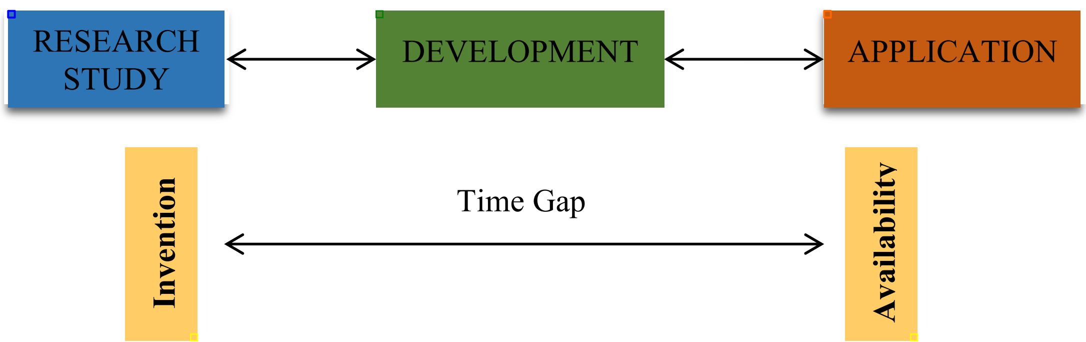

Figure 1.1: Time Elapsed from research pioneering to functional use of a new idea.

1.2. Problem Statement

In Reverse Engineering, conventional measurement methods such as 3D scanner, Moore projection, laser triangulation and coordinate measuring machine (CMM) are commonly used for accurate 3D data generation (Kumar et al., 2013; Singh, 2012; Varghese et al., 2018). However, these methods yield an enormous amount of irregular and scattered digitized point data that requires intensive processing in order to reconstruct the surface of the object.

Currently, the close-range photogrammetry technique practices on the used for smartphone cameras rather than relex cameras to capture images of physical object during investigation (Kaufman et al., 2015; Morales et al., 2015). This is because smartphones are more convenient to capture images but it may suffer from certain problems in data gatering, in the subsequent data processing. However, there are yet no clear-cut, overaching explanation to investigate the potential relevance of these aspects with 3D model results (Chikatsu et al., 2009). Therefore, factors including photogrammetry setups, focal length, grid system, resolution, exposure and smartphone camera calibration have to be investigated.

On the other hand, points or coordinate measurements using algorithms or mathematical modelling such as The Tight Cocone algorithm, The Ball-Pivoting algorithm, and Power Crust algorithm are intensively applied in both conventional methods and photogrammetric techniques (Aicardi et al., 2018; Zhang et al., 2018). However, this method requires large amount of computation and is sensitive to parameter configurations and are very complex to be used (Altantsetseg et al., 2017; Guo et al., 2016). Therefore, the need for simple mathematical equations instead that aids for effective photogrammetric data acquisition have to be explored widely and analysed to investigate the relative performance in terms of point data characteristics (uniform or scatter; density), accuracy and features preservation of the constructed 3D models.

A framework for 3D model reconstruction utilizes the fundamental notions of general topology so that the topological primitives can investigate the interactions of the spatial objects (Morgenthal et al., 2019). In general, current frameworks provide a systematic solution to reconstruct geometric model from the surface mesh of an existing object and are designed based on the proposed surface feature strategies allowing for reconstructions of all kinds of industrial products (Mahabot et al., 2017).

According to many reserachers, these frameworks can be very difficult to be used as guidelines at certain modelling case studies due to few reasons: (i) the framework is complex and challenging to be applied; (ii) requires costly in-built algortihms and equipment; (iii) very time consuming and (iv) complexity of the relationships (Balasubramaniam et al., 2018; Mahabot et al., 2017; Stig et al., 2012). To overcome these limitations, Zlatanova et al., suggested that every framework has to be designed with the shortest path as possible that can model an object accurately (Zlatanova, et al., 2004). However, the success of the aforementioned framework still relies on the complex algorithms and equipment (Choudhary et al., 2019; Mokroš et al., 2018). Opposingly, frameworks that are not incorporated in mathematical concepts would eventually produce low accuracy model due to modelling errors (Morgenthal et al., 2019). Therefore, a potential photogrammetric framework consisting of a simple mathematical concepts and important input factors can be designed. This can particularly be helpful to reconstruct the geometric model with high accuracy and capture high level information.

1.3. Research Objectives

The purpose of this investigation is to present the efficiencies by means of precision and accuracy in reconstructing 3D models. This is achieved by utilizing the close-range photogrammetry technique through a proper shooting strategy. In order to accomplish this aim, several objectives of the research are outlined as follows:

(i) To investigate the factors of focal length, exposure, camera resolution and shooting distance that facilitate effective data acquisition phase using close-range photogrammetry technique.

(ii) To develop simple mathematical equations of a system in which the equations helps for an improved modeling accuracy.

(iii) To verify a framework based on the studied photogrammetric data acquisition factors and proposed mathematic equations.

1.4. Research Scopes

Photogrammetry technique is the science and a technological potential of acquiring measurements of any entity by way of photographic images. Moreover, to obtain a thorough understandings on the workings and scopes of the photogrammetry, it is necessary to study on the basis beforehand becoming accessible to applications. Thus, several scopes of the research are listed as below:

(i) 3D models are constructed from a set of 2D photographic images using Autodesk ReCap software.

(ii) Close-range image acquisitions are focused on large and small-scale objects for target heights approximately less than 1800 mm.

(iii) Image acquisitions for indoor scenes are performed using smartphones with an embedded 5, 8 and 12 Mpixels camera.

1.5. Significance of Study

Photogrammetry is a science formed of technology exhibiting over a century of historical features and evolution (Linder, 2006; Schenk, 2005). Moving forward on the techniques employed in acquiring data from an object via images, the digital modelling have refashioned significantly from optical modelling to a current new and developed digitizing workflow (Remondino et al., 2013). Parallel to this, the photogrammetry techniques are practicable for any types of studies. Besides, anyone including non-experts can easily adapt and use these photogrammetric methods.

Aforementioned, information or data can be acquired instantaneously from photographs, whereby it is composed of non-contact measuring techniques that assist the modelling of 3D space acquisition via 2D photographs (Alsadik, 2014). With this in mind, this modern technological advancement can yield a remarkable accurate and high precision of 3D surface data and texture (Baltsavias, 1999; Kolecka, 2015; Sketchfab, 2015). Moreover, the photogrammetry provides a potential solution to the cost and time compared to previous old techniques (Kolecka, 2015). Therefore, this study outlines the used of close-range photogrammetry technique with developed image recognition strategies. The objectives of this research highlight on the solution to create a framework to produce accurate photogrammetric products. Additionally, the shooting parameters abstraction that developed the mathematics formulae are investigated to aid in the photogrammetry process for better digital modeling. These mathematical models are developed based on the variables that strongly influence the photogrammetric data acquisition period. In conjunction to the studied input paramenters, certain variables are also presumed to be fixed. Furthermore, smartphones are used to show how convenient the techniques are and capable in gathering 3D data based on its technical specifications. Moreover, modern photogrammetry software, which has simple user-interface, freely accessible and powerful modeling tools is utilized. Autodesk ReCap software was chosen to recognize, and digitize the sample objects in different case studies into a digital model. Consequently, the developed 3D models are investigated and imported into several CAE simulations for further simulation purposes

Moroever, to reconstruct precise 3D model from the photographs, numerous photographs of the object have to be captured for the digitizing process (Kenarsari et al., 2017; Remondino et al., 2013). Besides, the images of the object are taken at different heights in full loops to achieve greater percentage area of overlapping photos between them (Remondino and El-Hakim, 2010). Precisely, about 60% overlap between photographs is advisable to ensure better accuracy and a corrective relative arrangement for processing (AUTODESK, 2016).

CHAPTER 2

LITERATURE REVIEW

2.1 Reverse engineering (RE)

2.1.1 Preliminary

Reverse Engineering (RE) or known, as the back engineering is an ageing approach that fashion or develop a digitized computer model from an existing object. The process is facilitated via a capable computer-aided engineering that succour in engineering analysis and investigations (Eilam, 2005). This conceptualization has become a significant emerging discipline, whereby being demonstrative on numerous of tasks and researches (Singhal, 2014). Referring to the old methods, where designers used clays, woods, plasters and foam rubbers to shape their ideas, in reverse engineering patterns are revolutionized into engineering models and visualizations (Kumar et al., 2013). Furthermore, RE approaches enable the models to adapt into a real framework for investigation purposes. At certain studies, designing or modelling in CAD software becomes challenging, as the objects geometric shape becomes more complicated. Nonetheless, the RE provides a solution to abstract the object geometric information into a three-dimensional computer graphics. Accordingly, this is termed to as the part-to-CAD model process. Also, RE is an approach of replicating any existing objects such as parts, products and subassemblies in the absence of their drawings. Moreover, this approach defines its availability between systems that acquired interface (Singh, 2012; Wang, 2010).

As introduced before, reverse engineering is a practical approach of making 3D models or products through digital forms. Besides for engineering and industrial purposes, rehabilitation of cultural heritages or monuments and sculptures can be preserved (Singh, 2012). Thus, the RE also branches into the methodical sequence of steps in developing restoration studies and documentation data of antiquated objects with the connection between the engineering discipline and architectural importance (Kumar et al., 2013). Additionally, with the accelerating high-end computer systems and computer software platforms it is plausible to digitally stitch a large number of photographic images of an object that are captured in several full loops to produce 3D virtual representation (Singhal, 2014). Hence, the RE approach disintegrates and analyses an object in details to disclose any essential parameters or data, for enhancements and modification purposes. Above all, the reverse engineering is a far ranging approach in any engineering fields. Apart from that, the RE also facilitates the development of educational resources (Messler, Jr., 2013). With this in mind, the main objective of the reverse engineering is the reconstruction of objects with geometric shapes constituting of several surfaces and profiles (Raja, 2008). Moreover, these reverse techniques are capable to produce outcomes that are precise and accurate, and penetrates into mass-market (Singh, 2012). Furthermore, the RE platforms can be categorized as a process of defining a system to:

i. Produce a representation of a system in a higher level of abstraction or in another form.
ii. Investigate a system's interrelationships and their components.

Thus, it can be stated that the RE approach starts with the physical objects or products and it works its process through the design stages in the opposite direction to reach at the product definition. Accordingly, it acquires as much information on the conceptual design and ideas that were implemented to produce the particular object. Therefore, Figure 2.1 illustrates the reverse engineering process (Garcia et al., 2014). The RE process can be divided into four stages, whereby after the data from a particular object is acquired, a pre-processing stage is set. In this second stage, the RE approach does not alter the existing system or subsystem, it forms connectivity between points recognition by merging the point clouds and reducing the redundancies. Consequently, in the third stage the generated point clouds from the multiple views are segmented into 'free-forms' and 'regular' surfaces. These surfaces are then fitted to approximate the bounding surfaces (Gustav, 2013). Finally, the process is completed by the actual model development through figurative visualisation in RE software. The produced digital models are now available for investigation purposes. However, the quality of the reconstructed model depends on the acquisition phase.

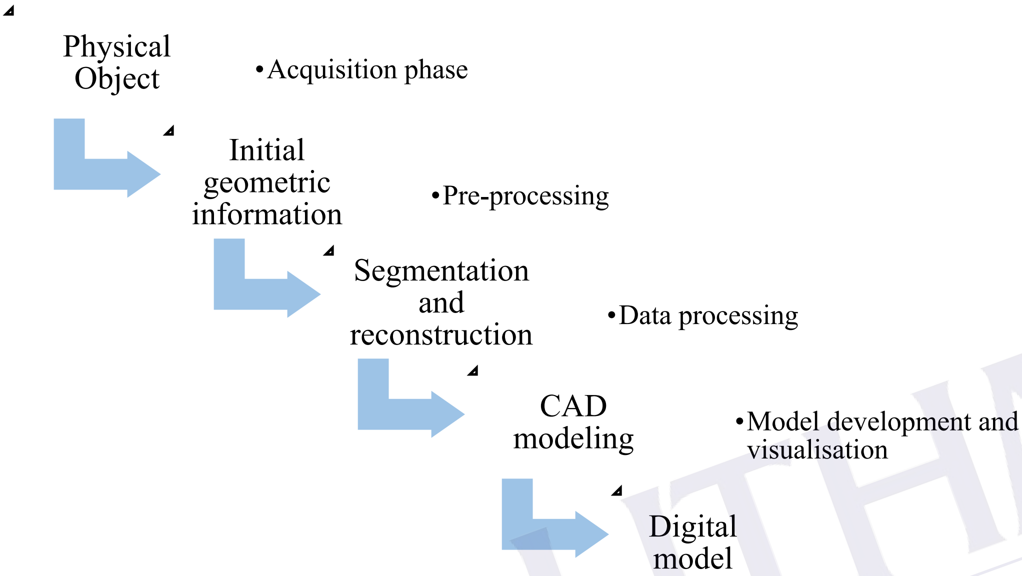

Figure 2.1: Fundamental stages of reverse engineering.

2.1.2. Historical background of reverse engineering

Reverse engineering has existed in many junctures in several centuries ago. The methodology of this concept has been practiced and experienced mostly by every small and large industries around the globe (Kumar et al., 2013). In the early 1930s, reverse engineering is commonly utilized in military terms during the World War Two and Cold War. It replicates foreign technologies, devices and information, which had been acquired by the armed forces and military intelligence (Wang, 2010). In 1984, the RE approach becomes one of the most popular discipline among researchers and stakeholders after the introduction of disk operating systems (DOS) by the Microsoft developer (Fu, 2008). Consequently, with the developments of computer technologies and systems, higher computational power, larger memory and high-speed connection between networks have attained a significant role in RE mainly in manufacturing and industrial applications over the past decades (Messler et al., 2013). On that account, the huge influence of reverse engineering in the business avenues has encouraged an industrial revolution. Most investigations from different fields have used the RE methods to achieve new forms of a new system (Raja, 2010).

2.1.3. Reverse engineering (RE) applications

Reverse engineering is very common in such various disciplines as automotive, aviation, consumer products, industrial manufacturing, research and development department, and mainly in diverse engineering fields. The development of new designs, software platforms, and the evolution, and enhancements on the products standards are the significant outcomes of the RE implementations. Here listed below are the several popular applications that uses the RE approaches:

(i) In aviation platforms

Aerospace companies such as Malaysia Aerospace Industry Association (MAIA), The Boeing Company and other related aviation companies vastly practice on the reverse engineering approaches. The utmost reasons are to remake digital inventories for aircrafts supply chain and transfigure legacy data into present CAD database. Therefore, these rapidly emerging aerospace and aviation industries apply the RE approaches are as follow (Fu, 2008):

(a) To develop legacy components and hard tooling, which do not acquire CAD modeling.
(b) To emend and rework issues prior from the deviation between CAD master model and the actual tooling or assembled part.
(c) To emend component's features and performances.
(d) To obtain competitive benchmarking of various design models in developing better components.
(e) To validate and verify quality and production models via computer-aided inspection and engineering analysis.

(ii) In software industry

The Institute of Electrical and Electronics Engineer (IEEE) has interpreted RE approaches in software application as "the process of extracting software system information form source code". The RE implementation enables high-level data or

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